handling unstable charged compounds had not been developed, and so it is not surprising that Woolley had difficulty in purifying the toxin.

How Does the Toxin Work?

The structure proof of wildfire toxin presented here will make possible the facile characterization of many related or identical toxins from various pseudomonad species. Their toxin structures may be of value in determining the relation between these species.

The novel structure of wildfire toxin encourages speculation on its mode of action. The β-lactam group has been found in nature only three times: in the penicillin series, in cephalosporin C, and in the pachystermines[24]. The unusually reactive β-lactam group found in wildfire toxin may well be essential to its toxic effect. Analogy to the proposed mechanisms of penicillin action[25] suggests that wildfire toxin exerts its biological effect by inhibiting some enzyme through acylation of the enzyme's active site.

Sinden and Durbin provided evidence that wildfire toxin inhibits the enzyme glutamine synthetase[14]. Methionine sulphoximine, biologically similar in most regards to wildfire toxin[13], is a glutamine synthetase inhibitor that is phosphorylated during its interaction with the enzyme[26]. This suggests that wildfire toxin is similarly phosphorylated during inhibition (Fig. 6). It should now be possible to investigate this question.

For two decades, work on wildfire toxin has proceeded with impure material of unknown structure. The solution to these problems makes possible a rational attack on the toxin's mode of action.

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Evidence for a Collapsar in the Binary System ε Aur

by

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The mysterious secondary component of ε Aur is probably not in a prestellar stage of evolution. It is more likely to be a black hole—a collapsar—formed by a stellar implosion.

EPSILON Aurigae is an eclipsing binary system with a period of 27.1 yr. Its primary star is an F2 supergiant with a mass of the order of 35 Suns. The secondary component is extremely unusual, and the system has long been regarded as very mysterious[1-3].

Ordinarily only lines due to the primary are visible in the spectrum of the system. During an eclipse some additional absorption lines associated with the secondary appear in the spectrum[4], indicating the presence of small amounts of dilute gas along the line of sight with an excitation temperature similar to that of the primary star. The secondary has a mass of about 23 Suns, however, and it would ordinarily have a luminosity of about 40% of that of the primary[2]. Clearly the secondary is not an ordinary star.

The eclipses are extremely unusual. An entire eclipse lasts just over 700 days, but during the central 330 days a remarkably constant 48% of the primary light is transmitted. The colour of the transmitted light is unchanged, and no polarization effects are produced. Kopal (ref. 2 and unpublished work) has argued convincingly that these effects can only be produced by the obscuration of the primary by a semitransparent disk of particles which are large compared with the wavelength of light. The disk must have approximately constant surface density, except near the outer rim, to produce the flat bottom in the eclipsing light curve. Previous suggestions that the obscuration might be due to solid particles were made by Ludendorff[4] and Schoenberg and Jung[5].

The primary and secondary are separated by some 35 astronomical units. The orbital plane is inclined to the celestial sphere by some 72°. If the occulting disk is oriented perpendicular to the line of sight it would therefore have a radius of some 12 a.u., and considerations of dynamical stability indicate that the radius is unlikely to be much larger than this.

How should this system be interpreted? It is evident that the secondary cannot be a star in any nuclear-burning stage of evolution. Kopal has suggested (unpublished work) that the ε Aur system is newly formed, that the primary star has not yet evolved onto the main sequence, and that the secondary is in a prestellar nonluminous stage of evolution in the form of a gaseous and dust-filled disk.

Unfortunately, there are compelling reasons for rejecting this model. A star of 35 solar masses spends very little time in its pre-main sequence contraction; in the vicinity of spectral class F its surface temperature should increase at a rate of 3 to 5 K per yr (ref. 6). This should readily be detectable. I have been investigating the physics of prestellar gaseous disks[7,8]. If a disk of 23 solar masses is formed with a radius of about 15 a.u., the initial gravitational collapse will heat the central regions to at least 10^4 K, and these regions will radiate with surface temperatures of several thousand degrees. Such an object is entirely excluded by the observations.

Alternatively the primary star could have evolved off the main sequence. In this case it is necessary to assume that the present secondary was originally more massive than the present primary. Thus the present secondary would have evolved off the main sequence somewhat earlier than the present primary. It would have undergone extensive mass loss in the red giant stage, and have come to a catastrophic end-point to its nuclear-burning lifetime.

A remnant mass of 23 Suns is much too large to correspond to a stable white dwarf or neutron star. The alternative is a nonluminous singularity, or black hole. I use the term "collapsar" to refer to that class of black holes formed by stellar implosion.

This form of remnant is entirely in accord with current predictions of supernova hydrodynamic calculations. Wilson[9] has found that the neutrino–antineutrino transport mechanism for envelope ejection in a supernova event is entirely inadequate to eject mass. Arnett[10] has discussed thermonuclear explosion theories of supernova events, but a star of main sequence mass about 50 Suns will burn carbon and oxygen before forming an electron-degenerate core, so that it cannot be disrupted by a thermonuclear detonation. Thus the bulk of the star which remains at the onset of the implosion is expected to participate in the general relativistic gravitational collapse.

If this picture is correct, the orbit of ε Aur gives useful information about the amount of mass ejection that could have accompanied the implosion. If half the mass had been ejected, the remnant would have escaped from the system. If even 10% of the mass were ejected, a quite elliptical orbit would have been produced. Kuiper, Struve and Strongren[1] determined an orbital eccentricity of 0.33, but a more recent determination by Morris[11] gave only 0.17. Because this would not have been an unusual eccentricity for the original system, it seems that not more than a few per cent of the mass could have been ejected at the time of formation of the collapsar.

I shall now consider the origin and nature of the solid particles orbiting in a disk about the collapsar. Mitchell[12] detected excess infrared radiation from ε Aur which was quite strong at 9.5 μm. He showed that this radiation was equivalent to that which would be emitted by a spherical surface of 50 a.u. in radius having a temperature of 500 K.

The F2 primary in ε Aur emits about 10^{39} erg/s. Black bodies which absorb unidirectional radiation and reradiate isotropically will therefore have a temperature of 500 K at a distance of 160 a.u. from the primary. The source of the infrared radiation would therefore seem to be a cloud of solid particles at a distance of 160 a.u. from the centre of mass of the system. Because these particles must approximately maintain this distance, they are probably present in the form of a large disk or ring covering a range of radial distances centred about 160 a.u.

Particles of small size will be ejected from the system by radiation pressure, and particles of somewhat larger size will spiral inward owing to the Poynting–Robertson effect[13]. As is conventional, let us define

$$\alpha = \frac{3L}{16\pi\rho a c^2}$$

where L is the stellar luminosity, ρ is the particle density, a is the radius, and c is the velocity of light. The critical particle size is given by the condition

$$G(M_1 + M_2) = \alpha c$$

where M_1 and M_2 are the masses of the two stellar components of the system. With $L = 10^{39}$ erg/s and $\rho = 3.5$ g/cm^3, the critical radius is $a = 0.20$ cm. When both components were on the main sequence, however, the luminosity would have been higher, and particles with radii as large as 0.5 cm were probably blown away from the system.

If all the particles have a radius of 0.5 cm, then the infrared source strength is equivalent to a total mass of 4×10^{30} g of solid material, which would be the chemically condensable component of one solar mass of material.

There has been about 2×10^{14} s during which the Poynting–Robertson effect can have been operating on this material. The time t for an orbit to collapse from an initial radius r is

$$t = \frac{r^2}{4\alpha}$$

The radius from which the present primary could bring in particles of 0.5 cm in 2×10^{14} s is 116 a.u., and this distance would be extended slightly, if allowance is made for the earlier additional contribution of light from the companion star. This result is entirely consistent with the previous conclusion concerning the location of the undisturbed particle reservoir.

As the particles spiral inward they will first come under the local gravitational influence of the collapsar, which lies farther from the centre of mass than the primary. Because the radiation drag experienced by the particles is a dissipative process, they can then be captured by the collapsar. For the particles to be captured dominantly into a plane nearby perpendicular to the line joining the binary components, it is necessary that this line be somewhat tilted relative to the plane of the initial particle orbits. The capture will take place at the time of greatest separation of the components in their orbits.

The captured particles will be maintained at a temperature of about 1,070 K in the radiation flux from the primary. This is sufficiently low so that evaporation of iron and magnesium silicates from the particles is not important.

The particles will spiral into the collapsar due to the continuing radiation drag. For a constant radiation flux incident perpendicular to the direction of particle motion, the particle radius r becomes

$$r = r_0 \exp(-2\alpha t/R^2)$$

where r_0 is the initial particle radius and R is the separation of the binary components. The particle orbits would shrink a factor two in about 8×10^5 yr. Thus there has not been time for any of the particles to have been absorbed by the collapsar.

Although this treatment does not predict a precisely constant surface density of particles in the disk about the collapsar, the departures from constant density are not great over the narrow range of disk radii involved in the eclipse. A more precise treatment is in any case required to determine the surface density near the edge of the disk where the capture takes place.

The model described here seems to account satisfactorily for the major observational features of the ε Aur system. Because of the intrinsically great interest in the possible discovery of a collapsar, it is recommended that much more observational attention be paid to ε Aur, particularly in the infrared. Improved orbit determinations are also very desirable, and continued photometric coverage during eclipses.

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Collapsars, Infrared Disks and Invisible Secondaries of Massive Binary Systems

by
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The supergiant primary of the eclipsing binary system ε Aur is probably a star of high mass burning helium in its core. Cameron's suggestion that the invisible secondary is a massive collapsar surrounded by a cool disk of solid particles is thus given further support. A similar object with a disk may be in orbit around the supergiant 89 Her, which has a large infrared excess of unknown origin. The disk could be formed during the initial stage of collapse of the secondary.

INTERPRETATION of the binary system ε Aur has always been hampered by observational difficulties. The system consists of a supergiant primary, with a spectrum which is most commonly classified[1] in the range A8 Ia to F2 Ia, and a peculiar invisible secondary. The orbital period is 27 yr, and the primary undergoes eclipses in which the light from the eclipsed star is never completely extinguished. The mass function of the system is 3.1 $M_\odot$.

Kopal (in unpublished work) has argued convincingly against earlier theories of ε Aur and has interpreted the secondary as a large semitransparent disk composed of solid particles, in a prestellar stage of evolution. Thus the primary would of necessity be a massive star in its pre-main-sequence phase of evolution, crossing the H–R diagram as a yellow supergiant. Cameron, in the preceding article, has criticized this interpretation on several counts, although he accepts the existence of the disk of particles. In his view, the primary is an evolved star of high mass, and the secondary, originally the more massive star, has completed its evolution and is at present a collapsar of extremely small radius; the disk (of small mass in Cameron's theory) has been accreted from the interstellar medium. Previously Trimble and Thorne[2], in their unsuccessful search among known binaries for a possible collapsed object, mentioned the companion of ε Aur as a possible candidate but rejected it on rather superficial grounds.

It has been assumed that the bright luminosity classification of the primary star implies a high mass. That this is not necessarily so can be demonstrated simply from the parameters which specify a stellar atmosphere: namely its chemical composition, effective temperature and surface gravity. Certain models of stars with initially low to moderate mass (refs. 3 and 4 and unpublished work of W. Deinzer) can, in very distended states of advanced evolution after mass loss, attain the specific characteristics of a yellow Ia supergiant. Furthermore, not only is their lifetime in this state comparable with the lifetime of a massive supergiant with the same spectral type, but in general, the birth rate of low-mass stars in space is very much greater than that of massive stars. If ε Aur were an evolved system containing two low-mass stars, then the disk around the secondary star could conceivably contain a main-sequence star, or a white dwarf, or even a neutron star. Because the mass of the secondary system is high (3.6 $M_\odot$) even in the limit of a very small mass of the primary, the disk would have to be fairly massive if a collapsar or main-sequence star is not embedded inside. Clearly it is important to establish the mass and evolutionary stage of the primary of ε Aur in order to interpret the secondary, and this is the object of this article.

The position of ε Aur on the sky is not far from that of the association of stars known as Aur OB1. The IAU[5] boundaries of the association are: $l^{II} = 168°$ to $178°$ and $b^{II} = -7°$ to $+4°$; ε Aur is located at $l^{II} = 163°$ and $b^{II} = +1.2°$. Several possible members of Aur OB1 have been listed by Morgan, Whitford, and Code[6] and by Humphreys[7]. To construct an accurate H–R diagram for the association, the stars listed by these authors and additional stars from Hiltner's[8] general list of OB stars lying within the formal projected boundaries of the association have been examined for membership on the basis of their radial velocities and apparent magnitudes. Radial velocities were taken from the catalogues of Wilson[9] and of Petrie and Pearce[10]; V and B magnitudes from Blanco, Demers,